INNOVATIONS FOR FUTURE GAP CROSSING OPERATIONS

Jimmy E. Fowler*, Donald T. Resio, James N. Pratt, and Stanley J. Boc
Engineer Research and Development Center, Coastal and Hydraulics Laboratory
Vicksburg, MS 39180

Francis E. Sargent
Quantum Engineering Design
Vicksburg, MS 39180

ABSTRACT

"Our ability to strike globally cannot be hampered by anti-access or area denial strategies employed by our adversaries." This excerpt from our National Military Strategy (NMS) describes one of the greatest challenges for today's and tomorrow's fighting forces. Even with the Army's transformation to lighter forces, problems in difficult terrains, such as coastal and riverine areas, soft soils, and man-made impediments can bring the flow of equipment and personnel to a standstill. Previous concepts have focused on three approaches: 1) crossing a gap with a bridging element that is supported at either end of the gap 2) filling the gap and possibly adding a bearing surface on top of the fill material and 3) crossing a gap with loosely connected floating rigid sections (such as the Modular Causeway System. However, none of the current gap-crossing systems can be employed in certain environments that are difficult to traverse, such as wetlands or mudflats. Recent research at the Engineering Research and Development Center (ERDC) has shown that a viable alternative to all of the existing systems can be achieved by utilizing the new concepts described herein.

ERDC researchers are presently developing gap-crossing technologies that use High Modulus Synthetic Fiber (HMSF) straps to achieve moment carrying capacities and increased survivability characteristics. The HMSF straps are ued in conjunction with designs that combine optimized geometric properties for gaining high moments of inertia for bending resistance and the ability to fold the structure in order to minimize storage volume and enhance transportability. Additionally, the unfolded structures utilize both local support (inflatable or structural) and optimized structural designs to carry arbitrary loads while minimizing system weight. These prominent and versatile characteristics allow the structure to be considerably lighter than previous systems, which will enable such structures to be air transportable. Successful demonstrations of both full-scale and sub-scaled models, as well as Finite Element (FE) models and analytical and empirical studies, have shown that this new approach to gap-crossing is not only feasible and robust, but can be extended to meet a range of potential military and civilian needs, such as dismounted rooftop to rooftop movement in an urban environment to ingress and evacuation routes after natural disasters such as hurricanes and tsunamis.

1. CAPABILITY GAP DESCRIPTION

Today's Army faces overwhelming challenges associated with access and maneuverability in strategic areas for conducting both ingress and egress logistical operations. Such areas include damaged or access-denied commercial ports, small ports with insufficient infrastructure that impede successful offload of personnel and materiel, and mudflat/soft soil terrains that are presently impassable by any existing gap-crossing system. Existing gap-crossing technologies, such as the Improved Navy Lighterage System (INLS), Modular Causeway System (MCS), and the Improved Ribbon Bridge (IRB), fall short of overcoming the obstacles outlined above. Furthermore, these systems are excessive in weight, have substantial limitations in storage volume, require intensive in-water assembly and substantial support equipment and materials onsite for employment, and are not air liftable/deliverable (with the exception of the IRB). Refer to Figures 1 and 2.

Figure 1. INLS requiring heavy-duty crane for handling.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 NOV 2006**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Innovations For Future Gap Crossing Operations**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Engineer Research and Development Center, Coastal and Hydraulics Laboratory Vicksburg, MS 39180**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002075., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**5**	

Figure 2. Photo of the IRB and delivery system.

These shortcomings render the existing systems insufficient for meeting the Army's demands for expedient, efficient, and successful gap-crossings in future theaters of operation.

2. SOLUTION

2.1 Lightweight Modular Causeway System

A viable solution engineers and scientists at ERDC have been developing is the Lightweight Modular Causeway System (LMCS). The LMCS is a new technology that has been part of a three year R&D effort and now a vital component of the Joint Enable Theater Access – Seaports of Debarkation (JETA-SPOD) Advanced Technology and Concept Demonstration (ACTD). The LMCS, depicted in Figure 3 below, is a viable means of achieving the Army's Force Projection and Maneuver operations in mudflat/soft terrains as well as an alternative means to damaged or inadequate ports for ingress operations.

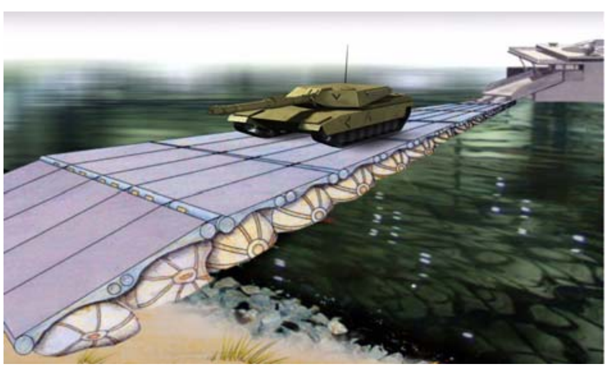

Figure 3. Artist's rendition of LMCS.

Key logistical features associated with the LMCS compared to existing military causeway systems include minimal storage/shipping volume (at least 50% less as shown in Figure 4), significant reduction in weight per linear foot of operational length (at least 50%), no in-water connections with minimal equipment/assets for emplacement, support of maximum payload equivalent to 74 ton M1A2 Main Battle Tank, and lengths tailorable to arbitrary gap lengths.

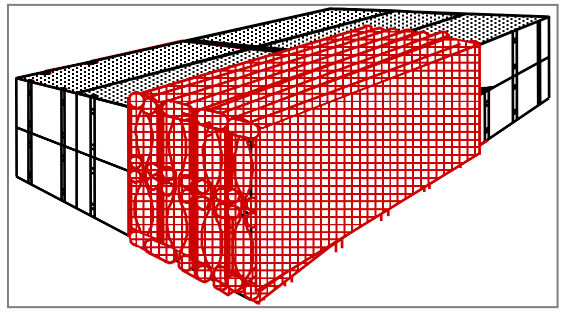

Figure 4. Storage volume of LMCS (red) compared to equivalent length of MCS.

In addition, the LMCS is being designed to be operational in sheltered ports and harbors under minimal sea-state conditions, to interface with existing Joint Logistics Over the Shore (JLOTS) watercraft, and to be air liftable/deliverable.

2.2 Innovative Concepts

Under the JETA-SPOD ACTD, the LMCS is presently being designed to be rapidly deployable and recoverable aboard a new class of military watercraft known as the Joint High Speed Vessel (JHSV). JHSVs are high speed, shallow draft vessels that can access smaller and austere seaports. Such SPODs are five times more abundant than world class ports. The LMCS will be deployable and recoverable aboard the JHSV using an automated Emplacement and Recovery (E&R) system unique to the LMCS, allowing expedient and safe operations with no in-water connections, continuous deployment of any required length, and emplacement/ recovery rates significantly faster than existing systems.

Two other technological advancements unique to this system include inflatable floatation for local buoyant support and the incorporation of the HMSF straps, which includes high strength materials such as Kevlar, Vectran, and Spectra. Integrated pre-packaged pneumatic tubes significantly reduce storage volume during transit/handling operations while attaining sufficient floatation for design load when employed in an operational theater. The incorporation of pneumatic tubes also largely contributes to the system's minimal weight. The HMSF straps/ropes as modular connectors, as shown in Figure 5, are a vital asset both logistically and technologically.

Figure 5. HMSF Twaron Orbit strap.

These connectors permit the modular structure to be pre-connected and foldable and attain continuous design stiffness once operational. The HMSF connectors also provide a degree of compliancy to the system when employed in a wave/current environment. Wave forces have plagued, and continue to plague, existing causeway systems that use hard/mechanical modular connectors that more easily fatigue and fail when subjected to such conditions. Extensive research carried out by ERDC engineers, as well as a series of laboratory tests, shows the HMSF connectors significantly improve sea-state operability and survivability of the LMCS.

3. THEORETICAL AND EMPIRICAL ANALYSSES

3.1 Analytical Examinations

Extensive analyses pertaining to closed form solutions, Finite Element (FE) modeling, and fundamental deformation relationships of a distributed loaded beam have been carried out by ERDC members. A Gram-Charlier series expansion, as shown in Equation 1, showed that a single term could provide an accurate closed form solution of s floating beam with continuous stiffness.

$$\frac{d^2y}{dx^2} = -2\mu y_o = \frac{M}{EI} = \frac{2\rho g \delta z \int_0^\infty (xy)dx}{EI} \qquad (1)$$

Using this approach, it was determined that there is a relationship between overall beam stiffness (EI), the net displacement of the system, and tension on connecting elements between causeway sections. As EI decreases, the displacement increases and the tension decreases. This solution confirms the numerical solution produced by Finite Element Analysis (FEA).

The FEA also allows optimization of the overall compliant and hardened structure. The model treats the displacement of floatation support as non-linear springs (although they are reasonably linear) on which the structure is applied to. The 3D FE model uses NIKE3D, and ABAQUS Standard analytical tools with LMCS design specifications based on the Trilateral Design and Test Code for Military Bridging and Gap-Crossing Equipment. The model generates results pertaining to detailed localized stress and vertical displacement values (including loss of multiple tubes local to payload), as well as localized gap openings between LMCS modules. Refer to Figures 6 and 7. The simulation for a symmetrically loaded joint involves HMSF straps supporting the tensile force and the structure supporting the compressive force. The 3D model simulates the actual behavior of the strap-stiffened joints between modules.

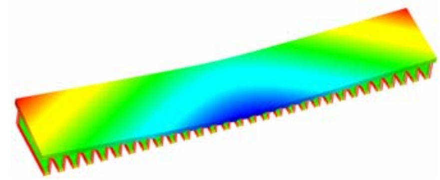

Figure 6. 3D FE model stress analysis on LMCS.

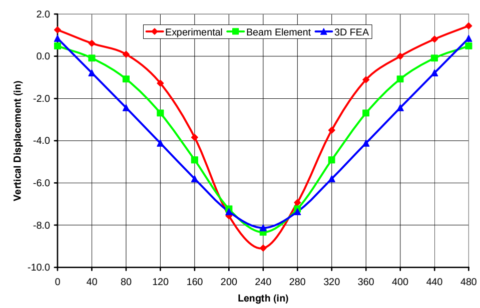

Figure 7. Load deflection for varying stiffness of LMCS.

Deformation relationships between structural and geometric properties enable the analysis and design of the compliant connections at discrete locations, as shown in Equation 2 below.

$$M = kD^2\theta \qquad (2)$$

The equation specifically represents a fundamental relationship between the moment carrying capacity, the stiffness and discrete location of the HMSF connector, and the deformation (gap-opening) between LMCS modules.

3.2 Laboratory and Mid/Full-Scale Studies

In addition to various analytical approaches, a series of laboratory and mid/full-scale studies have been conducted as well. Sea-state (SS) tests on two sub-scaled models were conducted in a wave basin at Oregon State University's Hinsdale Wave Research Laboratory. A 1:3 scale model representing 80 ft of causeway length was used for operational studies (payload equivalent to 74-ton M1A2 tank applied) at low/moderate sea-state conditions. Visual observations of the model's performance showed that the LMCS is at least equal to the operational capabilities of the Army's MCS. Empirical measurements of the excited forces from both the payload and the continuous wave activity in the load bearing HMSF straps showed the straps reached a maximum force of approximately 20 percent of the strap's Minimal Break Load (MBL), concluding that the load-carrying capability of the straps are suitable for operation in moderate sea-states. A 1:10 scale model representing 400 ft of causeway length showed that the compliancy of the system relative to the HMSF connectors offers great

promise for safely operating the LMCS in higher sea-states. Tests conducted at SS5 – SS6 (no payload applied) with significant wave heights up 20 ft and individual wave heights up to 34 ft clearly showed that the compliancy in the straps enhanced the system's survivability as the system remained fully intact throughout the study. These models are shown in Figures 8 and 9.

Figure 8. Operational study of 1:3 scale model.

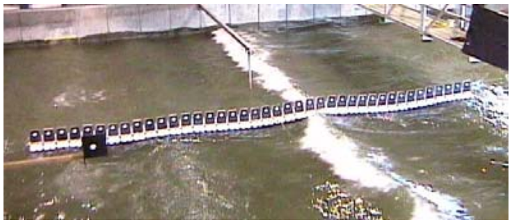

Figure 9. Survivability study of 1:10 scale model.

Two field demonstrations of 1:3 scale models successfully showed the system's ability to support the design load of a M1A2 tank. Measured deflections of vertical displacement and gap-openings, as illustrated in Figures 10 and 11, were consistent with results produced from the FE model. Moreover, multiple floatation tubes were deflated to demonstrate the impact on loss of freeboard, which was very minimal. This observation also correlated well with the FE model's predictions.

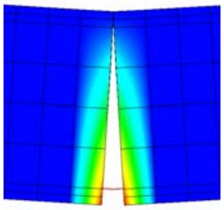

Figure 10. FE model depiction of gap-opening.

Figure 11. 1:3 Mid-scale model depiction of gap opening.

Field experiments were also conducted on prototype scale HMSF straps. Tests were conducted on Technora and Twaron Orbit (shown in Figure 5) straps, both comprised of twisted aramid fibers, to verify design stiffness and load capacity of designed configuration. Tests showed that Twaron fibers provided an optimal means to meet design requirements, and were consequently employed as the modular connectors in a recent demonstration of a full-scale LMCS model.

4. FUTURE LIGHTWEIGHT GAP-CROSSING CONCEPTS AND APPLICATIONS

4.1 Analyses for Future Concepts

A firm theoretical basis has been developed and validated for the analysis of general gap-crossing problems, as shown in Figures 12 and 13 below.

$$\frac{d^2y}{dx^2} = \frac{M}{EI} \longrightarrow \textbf{Bending for Simple Beam}$$

$$x_e = \left(\frac{EI}{\pi^2 \rho g \delta_z}\right)^{1/4} \longrightarrow \textbf{Joint Stiffness Equation}$$

$$E = \frac{\Delta F}{\Delta \varepsilon A} \longrightarrow \textbf{Tensile Modulus}$$

M = Bending Moment	EI = Dynamic Flexural Stiffness
E = Tensile Modulus	I = Moment of Inertia
X_e = Effective Moment Arm Length	ρ = Density
g = Gravity Constant	δ_z = Distance of load distribution
ΔF = Force	Δε = Elongatio

Figure 12. Pertinent HMSF strap design equations.

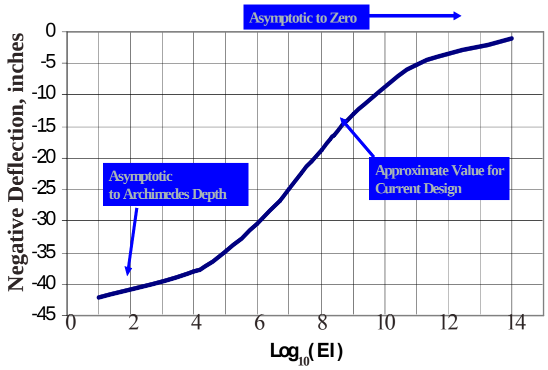

Figure 13. Vertical displacement vs. stiffness.

The design basis relies on strap-stiffened joints that can introduce other nonlinear behavior. The primary facets of this are the joint deformations and allowing the formation of gaps between deck sections. These analyses can be applied to examine specific problems pertaining to a wide range of scales, load requirements, and types of gaps, from mudflat to riverine crossings or landings.

4.2 Future Applications

Spin-offs of the LMCS technology can be used for a variety of important applications, both military and civilian. Potential systems very similar to the LMCS include a much lighter causeway system used for smaller design payloads such as Stryker vehicles. Such a system would weigh approximately 30 percent of the LMCS per linear foot and have a storage volume equal to that of the LMCS, but with twice the operational length. A similar system would be one that could rapidly emplaced across mudflats by being dragged by a rotary winged aircraft, a highly advantageous capability for any force projection maneuver. Figures 14 and 15 illustrate such potential applications of this technology.

Figure 14. LMCS suited for Stryker and lighter vehicles.

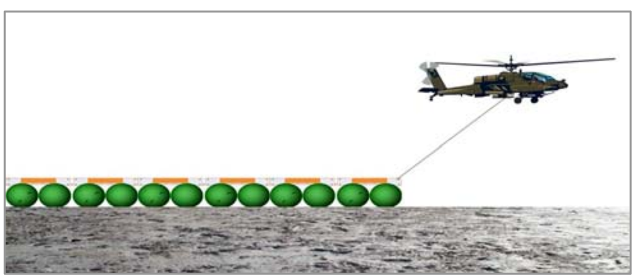

Figure 15. LMCS emplaced across mudflats via rotary winged aircraft tow.

Other potential systems include a foldable/expandable Soldier crossing unit, as illustrated in Figure 16, which could be utilized in rooftop to rooftop or steep narrow gap maneuverability.

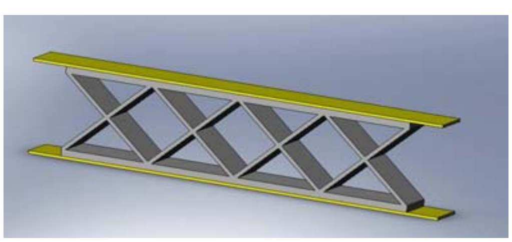

Figure 16. Illustration of foldable/expandable Soldier crossing unit.

Another highly beneficial application would be for natural disaster relief efforts, where rapid emplacement of temporary bridging can be accessible to areas affected by tsunamis, hurricanes, etc. All such applications incorporate the HMSF straps.

CONCLUSIONS

Engineers and scientists at the US Army Engineer Research and Development Center have successfully developed and tested a new volume and weight saving causeway system known as the LMCS. The LMCS has potential to be a national asset to the National Security and Homeland Security Programs since this system can be used as a temporary gap crossing solution for damaged or denied seaports, as well as access to areas impacted by hurricanes/tsunamis. In the event of blockage of inlets/channels by terrorists to disrupt the Nation's commerce and trade via the ports and harbors, the LMCS would establish the necessary connectivity between harbor end and vessels unable to access ports. The technical foundations developed for the LMCS offer the ability to provide a scalable system of solutions for gap-crossing requirements, for both military and civilian applications. Extensions of this technology offer promising enablers for overcoming a wide range of identified US Army and critical civilian capability gaps.

ACKNOWLEGEMENTS

The authors acknowledge Headquarters, U.S. Army Corps of Engineers, for authorizing publication of this paper. It was prepared as part of the JETA-SPOD Advanced Concepts Technology Demonstration Program and the Military RDT&E Program of the U.S. Army Engineer Research and Development Center's Coastal and Hydraulics Laboratory. The authors thank Quantum Engineering Design personnel for their help during this project.

REFERENCES

Tri-Lateral Design and Test Code for Military Bridging and Gap Crossing Equipment, 1996, Published in United States.